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ABSTRACT

The different approaches to the generation of power from solar energy may be roughly divided into five categories: distributed collectors; central receivers; biomass; ocean thermal energy conversion; and photovoltaic devices. The first approach (distributed collectors) is the subject of this module. The material presented is designed to familiarize students with: the breakdown of solar radiation into its direct and diffuse components; selected elementary principles of optics; the operation of two important solar thermal electric schemes--the central receiver and the distributed collector approach; several ways in which heat can be stored; and why there is a fundamental limitation upon the conversion of thermal energy to useful work. The module is divided into four sections with two appendices. Sections consist of: (1) an introduction; (2) discussions of solar radiation; (3) discussion of concentrating collector systems; and (4) conclusions which focus on the physical/economic limitations of solar thermal electric power generation. Reviews of elementary optic principles and heat/thermodynamics are presented in the two appendices. Two experiments (measurement of the direct component with a solar cell and set up of a long, linear concentrating collector to evaluate its concentration factor) and question/problem sets are included. (JN)

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SOLAR THERMAL POWER

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1. INTRODUCTION

a. The National Plan

The Energy Research and Development Administration (now in the Department of Energy) has prepared a comprehensive plan for energy research to provide for the nation's energy requirements. This plan, as presented in the document ERDA-49, projects that a total of 45 Quads (1 Quad = 10^{15} BTU) will be supplied by solar energy by the year 2020. This same projection calls for 135 Quads of energy from coal and nuclear power, requiring perhaps 600 1000 MW nuclear reactors and the annual consumption of 3-4 billion tons of coal. This large estimate for the U. S. energy consumption can be questioned. But it is apparent that solar electricity is now being counted upon to provide for an appreciable fraction of our energy use by the year 2000. This is a remarkable turnabout from the prevailing sentiment of ten years ago that using the sun's energy was only a romantic dream of those who preferred to return to a more primitive existence.

b. Solar Heating and Cooling

It has long been realized that, despite the low energy density of the incoming insolation, solar radiation has a large potential as an energy source. The solar energy falling upon the roof of a typical residence is roughly ten times as great as the annual heat demand for that house. If we consider the fact that almost 25% of the nation's use of energy resources goes for space and water heating and cooling, it is apparent that rapid development of this aspect of solar energy applications could soon make a significant impact upon the U. S. energy budget.

There is a substantial base of research upon which the application of solar energy to space heating and cooling can be built. This

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is due to the solid technical base provided by the results of flat-plate collector and solar house experiments over the past 35 years. Further development work will be aimed at technical improvements such as freeze protection, selective surfaces, reducing the economic cost of solar components and improving their long-term efficiency and reliability. Considerable research effort also needs to be done on such topics as specialized approaches for specific climatic regions, the possible use of heat pumps, passive solar houses and heat-actuated refrigeration devices. Nevertheless, the basic technology for the rapid development of the solar heating and cooling industry is available and is presently either already competitive with conventional approaches or on the verge of being competitive in most areas of the country.

c. Generating Electricity from Solar Energy

No such sound technological base exists for the larger-scale development of solar power and electricity. While many different small solar engines have been constructed over the past 100 years, a very large amount of technical effort remains to be done in order to develop economic solar electricity. The different approaches to the generation of power from solar energy may be roughly divided into the following categories:

1. Distributed Collectors. Thermal energy is converted into electricity with the aid of a large number of solar collectors operating in tendem. In most approaches, the incident radiation is concentrated by a factor of 10-100, giving temperatures of 100-500° C for the operating fluid.
2. Central Receivers. A heat-exchange fluid located on top of a tall tower is heated by the solar energy reflected from

thousands of individual mirrors which track the sun (heliostats). This approach would involve concentrating the incident solar intensity by a factor greater than 1000. The resulting elevated fluid temperatures permit a high thermodynamic efficiency for the conversion of thermal energy to useful power. Figure 1 shows the mirror array for the solar tower facility at Sandia Laboratories in Albuquerque, New Mexico.

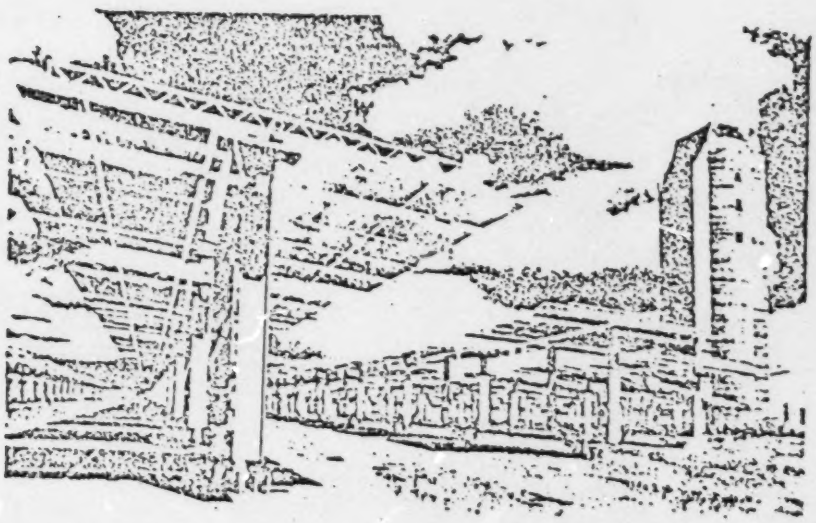


Fig. 1 Showing the tracking mirrors for the 5-MeV solar tower facility at Albuquerque, New Mexico.

3. Biomass. Photosynthesis is nature's way of converting solar radiation to a useful form. Many different schemes for extracting the energy from biomass are presently under study.

4. Ocean Thermal Energy Conversion: In this approach

power will be generated in a turbine driven by the small temperature gradients present in the ocean between the surface and the water at depths of hundreds of meters.

5. Photovoltaic Devices. The direct conversion of solar radiation into electricity using solar cells. A massive Federal program is now underway to reduce the cost of solar cells, which is presently prohibitive for everyday usage.

Only the first approach is discussed in this module.

d. Prerequisites

The material in this module is presented at a level which should be understandable to anyone with some background in high school physics. This background should include familiarity with concepts of energy, the laws of thermodynamics, and geometrical optics. In order to work the problems, an elementary understanding of wave motion and mechanics would be useful, and a high school background in algebra and trigonometry is presumed.

e. Goals

1. To become familiar with the breakdown of solar radiation into its direct and diffuse components.
2. To understand a few elementary principles of optics.
3. To study how two of the important solar thermal electric schemes, the central receiver and the distributed collector approach, work.
4. To become acquainted with some of the ways in which heat can be stored.
5. To understand in a rudimentary way why there is a fundamental limitation upon the conversion of thermal energy to useful work.

SEGMENT I

2. SOLAR RADIATION

a. The Solar Spectrum

The radiation from the sun, while approximating that from a black body differs slightly due primarily to structure in the surface emitting region and to absorption in gases at the surface. For most purposes it will be adequate to consider the sun as a perfect radiator emitting at a temperature of about 6000° K (≅ 11,000° F). The wavelength range of 300 to 4000 x 10^{-9}m (10^{-9}m is called a nanometer) includes most of the energy of the solar radiation. The spectral distribution of the energy emitted by the sun is of particular importance to the useful collection of solar radiation because of the dependence of the reflective and absorptive properties of materials such as glass and various metals upon the wavelength of the radiation. The distribution of the amount of solar energy incident upon the earth as a function of wavelength is shown in Figure 2. About 80% of the total incident solar radiation lies in the wavelength region which is transmitted by ordinary glass.

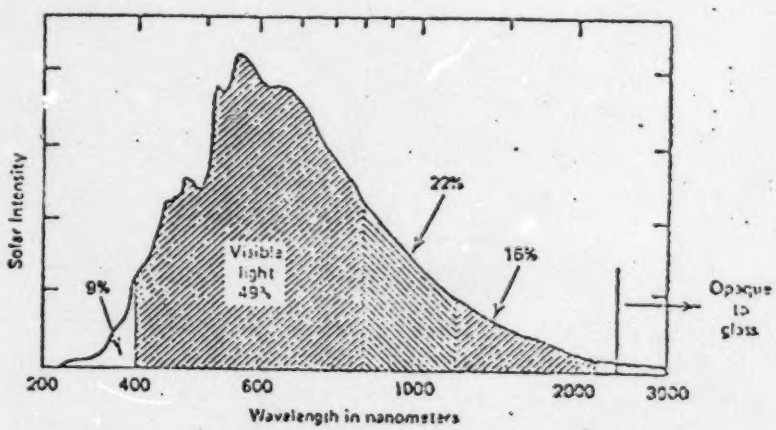


Fig. 2. Division of the intensity of the solar spectrum into its different wavelength regions.

The radiation from the sun can be separated into three main energy regions:

1. The short-wave length radiation at the left of Figure 2 is called ultraviolet or UV radiation and is not visible to the human eye. These are the rays that produce our suntan or sunburn. A considerable amount of the UV radiation which enters the outer atmosphere is absorbed there and does not reach the earth's surface.

2. The middle wavelengths in Fig. 2 are referred to as the visible spectrum, since these are the wavelengths which can be seen by the human eye. When this light, which appears white to our eyes, is passed through a specially constructed triangular piece of glass called a prism, the varying speeds at which these wavelengths travel cause it to be broken down into colors that vary from violet through the blues and greens to the reds. The visible spectrum is an extremely narrow band when compared to the ultraviolet and the infrared regions, which extend far to the left and right of the region shown in Fig. 2.

3. The long-wavelength is referred to as infrared radiation (IR), or heat radiation, although the latter term is not a good one since the entire spectrum of radiation can heat an object. Practically any object can be considered to be radiating infrared, even a cake of ice. The amount of infrared radiated will depend on the item's temperature. Materials with a temperature below 800° F emit only infrared, with no visible or ultraviolet radiation. Thus, the radiation emitted from surface temperatures below 800° F is quite different in quality from the radiation of the sun.

A solar collector absorbs radiation from all three of these regions. The ultraviolet and visible, as well as infrared, are converted into heat on the surface of the collector.

b. Units of Measure

Because the United States has not yet accepted the metric system it is often necessary to convert from English to metric units or vice-versa. The following tables are provided to allow ready conversion of energy and energy density among the commonly used units.

Table 2. Energy Conversion Factors

	Joule	Btu	kWh
Joule(J)	1	948×10^{-6}	278×10^{-9}
Btu	1054	1	293×10^{-6}
(kWh) kilowatt-hour	3.6×10^{6}	3413	1

Table 3. Energy Density Conversion Factor

	Btu/Ft^2	kJ/m^2	Langleys
Btu/Ft^2	1	11.34	0.271
KJ/m^2	0.088	1	23.9×10^{-3}
Langleys (cal/cm^2)	3.69	41.84	1

c. Nature of Solar Radiation

While the earth intercepts only a small fraction of the total radiation emitted by the sun, the amount received per year is equivalent to tens of thousands times the present annual energy requirement for the world. Knowledge of the incident solar flux is clearly needed for most solar energy applications. The total solar energy of all wavelengths received per unit area of surface oriented normally (perpendicularly) to the sun's rays at the top of the earth's atmosphere is called the solar constant. The radiation incident upon this surface is illustrated in Figure 3. Since by definition this surface is always oriented perpendicular to the incoming solar radiation, the amount of energy received by a given area of surface should be independent of the time of year. This is the reason for calling the energy received per unit time the solar constant. The determination of this constant has been the object of a number of experimental measurements over the years. The earliest determinations, made from high mountains, had to be corrected for the transmission through the atmosphere of the different wavelength portions of the solar spectrum. More recent measurements with high altitide aircraft, balloons, and spacecraft have permitted direct determinations outside of most of the earth's atmospnere. The most recent value for the solar constant is 1373 W/m^2 (1.966 cal/cm^2-min, 435.5 Btu/ft^2-hr.)

Exercise 1.

Calculate the equivalent value of the solar constant in cal/cm^2-min and BTU/ft^2-hrs. (Answers to all exercises are given on pg. XX.)

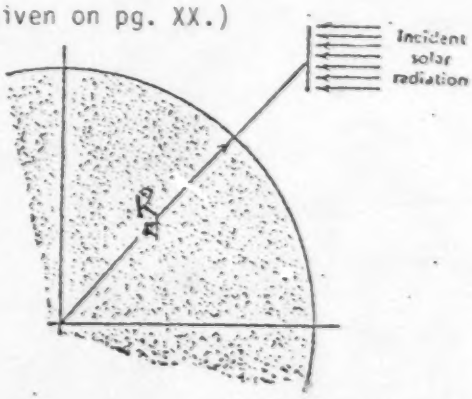


Fig. 3. Illustrating the meaning of solar constant. This is the amount of energy incident per unit time upon a unit area oriented perpendicular to the sun's rays at the top of the earth's atmosphere.

It is more precise to say that the solar constant as defined above is determined at the average distance between the sun and the earth. The orbit of the earth around the sun, though close to circular, is actually an ellipse. This causes a variation of the solar intensity of the order of ±3.3%. The maximum intensity upon a surface oriented perpendicular to the sun's rays occurs in December, reaching 1.033 times the average value (the solar constant). The minimum value occurs in June when the intensity is 0.967 times the average value. Minor fluctuations in the sun's radiated solar energy of the order of ±1% have also been claimed.

d. Direct and Diffuse Components

From the standpoint of practical applications of solar energy one is interested in the intensity and spectral distribution at the earth's surface. In principle, one could start with the solar constant and obtain the solar radiation intensity at ground level by correcting for the attenuation in intensity due the air mass and cloud cover of the atmosphere. This approach is seldom useful in practice due to large uncertainties in making the corrections, particularly that for the attenuation due to clouds. The most reliable way to determine the solar intensity on the ground is by direct measurement. Most commonly a measuring device called a pyranometer which measures the total solar radiation (called global radiation) incident upon it, is used. One type of pyranometer is shown in Fig. 4. The receiver consists of two concentric rings. The outer ring is white and the inner ring is black. The rings are often made of 0.25 mm thick silver foil, and the coatings are magnesium (white) and Parson's black. A thermal insulator is inserted between the rings. The dull, black surface absorbs almost all the radiation incident upon it, while the white magnesium oxide reflects visible and near-infrared radiation. The energy absorbed by the receiver generates a temperature

difference between the rings, and this temperature difference is then measured by a number of platimum-gold thermocouples.

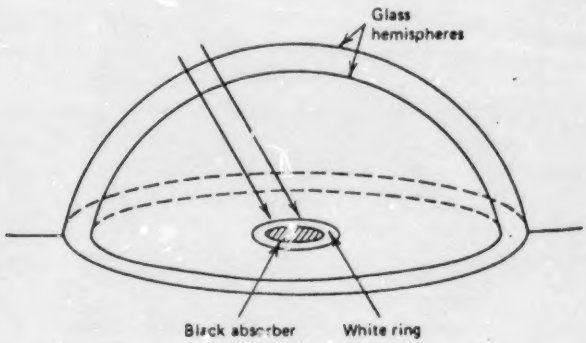


Fig. 4. Pictorial representation of a pyranometer.

While this measurement of the total solar intensity is useful it has some serious drawbacks for many specific applications.

(1) The solar radiation reaching the earth's surface consists of a direct beam from the sun plus a certain amount of scattered radiation (we call this the diffuse component). This breakdown is illustrated graphically in Figure 5.

The pyranometer does not distinguish between these components. Measurements of both the direct and scattered components have not usually been available in the past so that a combination of measured data and empirical procedures is commonly used.

(2) Most meteorlogical stations orient their pyranometers parallel to the horizontal plane so that it sees the entire sky. However, for space heating and cooling applications, the desired quantity is more often the solar intensity upon a tilted surface.

(3) Solar electric applications require a knowledge of the direct component of the solar intensity. This is needed because only the direct radiation can be focused by optical means, thereby permitting the solar intensity to be concentrated.

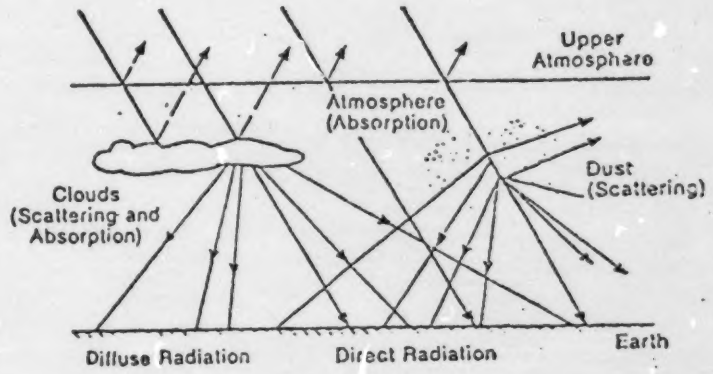


Fig. 5. Atmospheric effects on solar radiation reaching the earth's surface.

e. Statistical Procedure of Liu and Jordan

The total solar radiation can be measured with a pyranometer and the direct component can be measured with a collimated solar radiation detector called a pyrheliometer (see the module on solar heating by F. C. Bason). However, most of the time this data is not available and one must utilize only the total solar radiation data. In the early 1960's Liu and Jordan of the University of Minnesota developed an empirical procedure for estimating the diffuse and direct fractions of the incident solar intensity, working only from a knowledge of the total intensity on a horizontal surface.

As an aid in doing this they introduced a parameter called the sunshine index, K_T. Formally, the sunshine index is defined as the ratio of the measured total radiation upon a horizontal plane of the earth's surface to the corresponding quantity at the top of the atmosphere. That is,

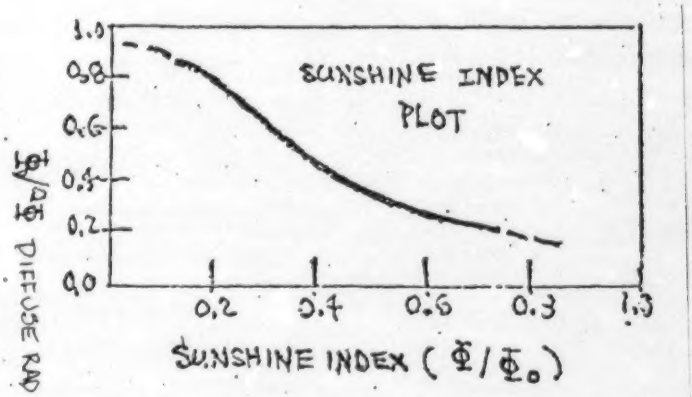
$$K_T = \phi/\phi_0,$$

where ϕ_0 is the insolation upon a horizontal surface at the top of the atmosphere, which can easily be calculated from a knowledge of the solar

constant. This parameter was then empirically correlated with the diffuse component obtained from data from recording stations which also recorded both the direct and total solar radiation. From a statistical analysis of this correlation, Liu and Jordan discovered that a firm relationship existed between K_T and the diffuse component. This relationship is graphically illustrated in Figure 6 for the case where monthly averages were used in the analysis.

The highest plotted values of K_T were near 85% indicating that under total clear sky conditions about 15% of ϕ_o was lost due to scattering and absorption by the atmospheric air mass alone. At the other end of the curve where K_T is about 5%, the diffuse percentage is about 100%.

Fig. 6. A graph of the empirical relation found by Liu and Jordan between the fraction of diffuse radiation and the sunshine index, K_T. All radiation values are averages calculated on a statistical basis.



In this case almost no direct sun is seen; the cloud cover required for this condition is very dense -- perhaps 4-5 miles deep. The relation outlined in Figure 5 is not strongly dependent upon latitude or other factors peculiar to a particular location. Using this graph the diffuse and direct solar components can then be estimated as follows:

1) Obtain ϕ, the total energy received upon a horizontal surface, from the measured data obtained with a horizontal pyranometer.

2) Compute ϕ_o, knowing the solar constant, the latitude, and the time of the year.

3) Compute $K_T = \phi/\phi_o$, the sunshine index which is the abscissa of Fig. 6.

4) From Figure 6 obtain ϕ_D/ϕ, the percentage of diffuse radiation.

5) Knowing the ratio ϕ_D/ϕ, one can then obtain the absolute amount of diffuse radiation by multiplying this ratio by ϕ.

6) The direct component ϕ_{DIR} is then obtained as

$$\phi_{DIR} = \phi - \phi_D.$$

f. Experiment: Measurement of the Direct Component with a Solar Cell

1) Discussion

High quality solar radiation measurements are an expensive proposition. For example, an Eppley PSP pyranometer costs almost $1,000, while measurement of the direct component of the solar radiation with an Eppley normal incidence pyrheliometer requires an expenditure of about $2,000 for the measuring instrument and tracking mount (needed to automatically follow the sun). In addition, accurate recording instruments can cost as much as

$1,000. In this experiment, we utilize an inexpensive solar cell to measure the total solar intensity, and the empirical procedures described above to determine the absolute intensity of the direct component.

A solar cell responds to visible light by producing an electric current. We will measure this current, using the simple apparatus shown in Figure 7, and then translate the measured current into a solar intensity by one (or both) of the two methods described below. The resistor R in Figure 7 is quite small, of the order of 10 to 50 ohms, so that the measurement of V(t) can be converted into a measurement of the (short circuit) current from the solar cell. Converting this current reading into a measurement of the solar radiation intensity can then be done in several ways; two possible methods are described in the next section.

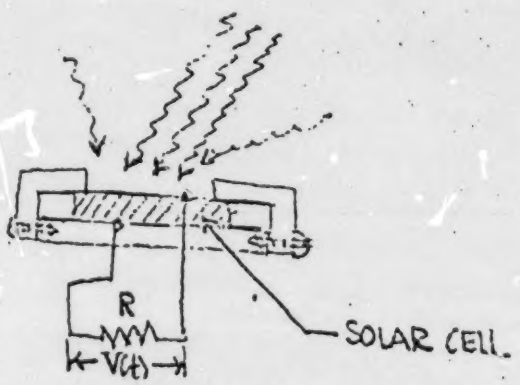


Fig. 7. Illustration of solar cell and mounting arrangement for a measurement of the solar intensity.

2) Procedure and Data Analysis

For reasonable precision to be attained it is necessary to make measurements of V(t) during an entire clear day with a good (high input impedance) voltmeter. The measurements should be made as often as possible, but on a good clear day V(t) readings at one-half hour intervals will suffice.

The simplest way to convert these readings into a solar intensity

measurement is to use the manufacturers data on short circuit current as a function of intensity. Usually this data is available in terms of a stated I (t) at a given radiation intensity, ϕ_o. Then, the intensity ϕ at any time is given as,

$$\phi(t) = \frac{I(t)}{I_o(t)} \phi_o.$$

By converting the V(t) data into $\phi(t)$, the resultant curve for the day can be integrated numerically to give the solar radiation received during the day. This approach should be good to about 10-15%.

A somewhat more complex approach is to calibrate the solar cell against some type of good quality instrument. For example, pyranometer data obtained from a nearby site (or city) with approximately the same climatic conditions should suffice to a precision of 10% or better.

The solar intensity is then obtained by determining the calibration constant of your solar cell. This is best done on a clear day, providing maximum readings and minimizing the effects of noise on the results. The measured I(t) data is plotted as a function of time over the entire day and the daily ampere-hour totals obtained by numerical integration. (Approximate the area under the I(t) vs. t curve by a series of 1/2 hour-wide strips.) The calibration constant is then obtained as

$$K = \frac{\text{Solar Insolation (Langleys, Btu/ft}^2\text{, kJ/m}^2\text{)}}{\text{Measured ampere-hours}}$$

Once the solar cell calibration constant has been obtained, the solar radiation received over any time interval can be obtained by measuring the ampere-hours obtained with the solar cell over the given time interval and multiplying the result by K.

The direct component on a horizontal surface on any day is then obtained by measuring the number of ampere-hours over an entire day, and

converting to solar intensity units by multiplying by K. With the aid of Figure 6, the direct and diffuse components are found as described in the previous section.

g. Questions and Problems

1. Describe the difference between direct and diffuse radiation.
2. Describe the effect of seasonal variations.
3. As a check on your background and your reading of the material indicate whether the following questions are TRUE or FALSE.
   a) Infrared radiation waves are longer than ultraviolet waves.
   b) The sun produces the greatest amount of energy in the visible range.
   c) Solar energy on a horizontal surface will show month to month variations.
   d) Light from the sun passes through a larger thickness of atmosphere in the early morning.
   e) The intensity of solar energy on a vertical surface is the same as the intensity on a horizontal surface on the same area.
4. What is the angle of the sun above the horizontal plane at solar noon on December 21 at your latitude? Repeat this question for the sun angle of solar noon on June 21. No complicated trigonometric equations need be used for this problem.
5. Use Tables 2 and 3 to make the following conversions:
   a) 80×10^6 Btu to Joules (This is the amount of energy needed to provide for the annual space heating needs of a typical dwelling.)

b) 80×10^6 Btu to kWh.

c) 20,000 kWh to Btu.

d) 600 Langleys to KJ/m^2.

6. The average total radiation upon a horizontal surface is measured to be 48.9 watts/m^2. (A watt is a Joule/sec.) The extraterrestial radiation can be calculated to be 143.7 watts/m^2 (on the average, of course). What is the sunshine index, K_T?

   Knowing this, compute ϕ_{DIR} and ϕ_D.

7. Let us now repeat the above problem using English units. Do this in the following steps.

   a) Calculate the insolation ϕ upon a horizontal surface in units of Btu/ft^2-Day.

   b) Calculate the extraterrestial radiation ϕ_o in the same units.

   c) What is K_T.

   d) Compute ϕ_D.

   e) Next, what is ϕ_{DIR}.

SEGMENT II

Note: The following discussion assumes that you are familiar with the principles of geometrical optics. If you would like a review, the important concepts needed for understanding the following material are presented in Appendix A of this module.

3. CONCENTRATING COLLECTOR SYSTEMS

a. Concentrating Systems

The amount of solar radiation received by an object can be increased through the use of refractive lenses or by the use of reflective mirrors. These two approaches are illustrated schematically in Figure 8. The two systems shown (or other such types) can use either cylindrical reflectors or refractors in order to achieve a "line focus", or they can use circular reflectors or refractors which focus radiation on a "point focus".

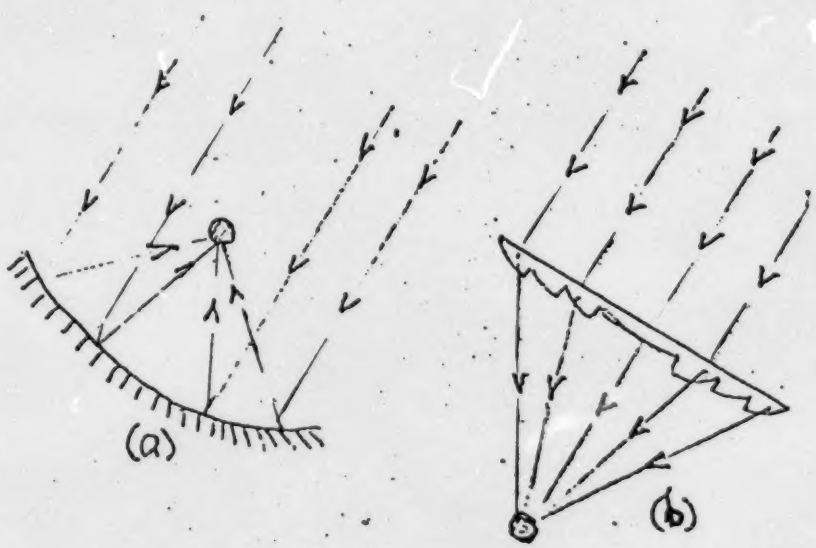


Fig. 8. Illustrating the principles of focusing systems. In (a) a parabolic reflector is used to effect a concentration of the incident solar flux, while in (b) a fresnel (converging) lens system is used.

A characteristic of primary importance is the concentration factor by which the energy density of the incident radiation is increased. This factor is practically identical to the geometrical area of the receiver. Concentration ratios for circular reflectors are clearly much higher than those for cylindrical types. However, point focusing devices require two-axis tracking mechanisms while the cylindrical ones only require single-axis tracking to follow the sun.

b. Intermediate Temperature Systems

Point focusing systems can reach very high temperatures. This is because the high concentration factor achieved gives a very high energy density at the receiver. Common sense tells us that higher temperatures will result from higher energy densities, but the relationship is far from linear. Detailed calculations give the results portrayed in Figure 9.

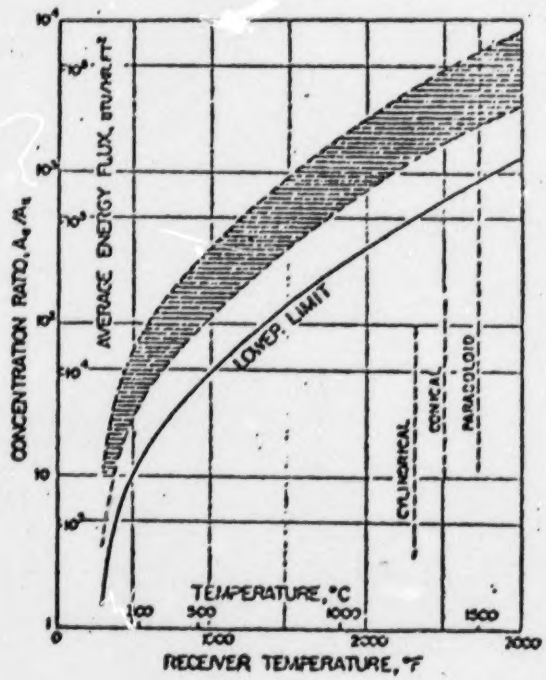


Fig. 9. This figure shows how the receiver temperature varies with the concentration factor. The shaded range corresponds to collection efficiencies of 40-60%. (Duffie and Beckman, John Wiley and Sons, Inc. 1974).

The point focus concept is utilized in the solar tower approach which is described later. In this case, resultant temperatures near 1000°C are achieved. An approach which is intermediate between the highly concentrating solar tower concept and the non-concentrating flat-plate collector is to use a series of distributed collectors, each of which has a modest concentration ratio, to collect the solar energy by heating a fluid to some moderately high temperature, usually in the 100-500° range. The basic idea involved here is certainly not new, having been utilized by a number of others in the early part of the 20th century, such as the Shuman and Boys power plant in Egypt which developed 50 horsepower for an irrigation project. However, these early engines all suffered from very low overall efficiencies (ratio of energy output to energy input) of the order of 3-4%.

Modern technology offers the possibility of a number of improvements over earlier solar designs. Moderate concentration ratios can be obtained through the use of well-constructed parabolic reflectors. These can either track the sun and focus the sun's rays upon a stationary receiver or, alternatively, a stationary reflector can be combined with a movable receiver. Losses in the receiver can be minimized through the use of modern techniques such as an evacuated inner element combined with a selective surface. This would eliminate convective losses and greatly reduce radiative emission in the infrared from the hot fluid. In either case, a single-axis tracking mechanism is utilized.

c. Principles of Operation

A simplified version of this type of solar collector is shown in Figure 10. The incident sunlight is brought to focus on the receiver with the aid of a long cylindrical parabolic reflector. The solar energy density is

concentrated by the factor X, where

$$X = \frac{2L}{d}$$

The solar energy density incident upon the receiver pipe is equal to $X\phi_o$, where ϕ_o is the incident solar energy density from the sun. Just as with a solar thermal collector for space heating, the receiver surface will warm up as it absorbs energy, and losses due to conduction, convection, and radiation can occur. For simplicity, we will assume that with an evacuated glass envelope the conductive-convective losses are zero. As the receiver pipe warms, it will radiate infrared radiation to the glass envelope which will also warm up and radiate. The outer glass envelope serves to cut down losses to the outside by reducing the effective temperature of the surface in contact with the outside atmosphere. One would like to run the receiver at as high a temperature as possible in order to increase the engine efficiency permitted by the second law of thermodynamics. On the other hand, the higher this temperature, the larger the energy that is reradiated by the hot receiver fluid. Actual operating engines will strike a compromise depending upon the type of use of the device. Overall system efficiencies in the 10-15% range are attainable.

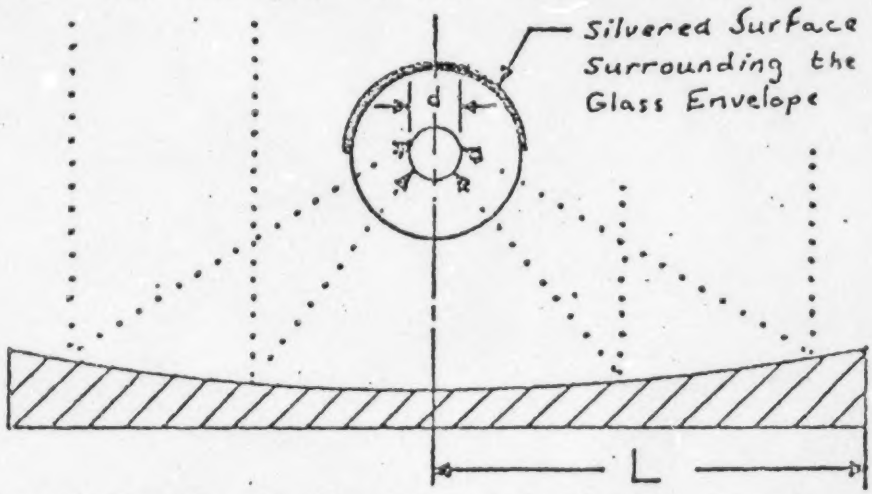


Fig. 10. Cross sectional view of our simple collector design.

d. Solar Towers

Curved parabolic reflectors have been used to concentrate the sun's radiation, both in solar ovens and in small solar furnaces, some of which have achieved temperature of 2000°F. The solar tower concept involves the collection of solar energy from a large field of mirrors in order to achieve the required high temperatures to produce steam to be used in electric power generators. The optimum arrangement for attaining very high temperatures is with point-focusing. To illustrate the size of a 100 MW facility, the surface area covered by the mirror field would be about one square mile and the tower height required is about 300 meters.

The development of large solar furnaces in France under the direction of Felix Trombe was a precursor of the present power tower effort. Trombe constructed his first solar furnace at Fort Mont Louis in the French Pyrenees. The sun's rays were reflected by a large flat mirror which tracked the sun, onto a stationary concave reflecting surface about 10 meters in diameter. The solar energy was then focused by this parabolic reflector to a small image where 75kW of heat were developed. Following this, Trombe constructed an even larger, 1-MW solar furnace at Odeillo, France. In this device the sun's rays are reflected by heliostats (steerable flat surface mirrors) located on the side of a hill upon a parabolic concentrator designed as an integral part of a nine-story building. The parabolic reflector is 115 feet high and 165 feet across. This was once the largest solar furnace in the world and has recently been converted to a solar electric generating facility.

For use in very large-scale systems, parabolic concentrators should be avoided because of size and expense. Instead, a large array of standard reflecting elements will be used. A typical system would consist of a small

heliostat mounted on a pedestal and positioned by an individual automatic control system. Each reflecting mirror then images the sun onto a fixed surface. The pedestal supporting the mirrors would have two degrees of motion providing rotation and tilt. Each morning the rotation and tilt positions on each mirror would be indexed to its proper position, and the automatic control system then maintains the reflected energy on the receiver located at the top of the tower. For aerospace companies used to designing highly accurate tracking mechanisms for ballistic missiles, the degree of accuracy required here can be easily and inexpensively attained.

The first step in the federal research and development program is the completion and testing of a 5-megawatt thermal (5Mwt) facility located near Albuquerque, New Mexico. A picture of this $21 million facility is presented in Figure 11. The tower is 200 feet tall and was constructed from 5700 cubic yards of concrete. Each heliostat is anchored with nine 10-ton concrete footings and the entire mirror field will cover 100 acres. The next stage in the Federal development program is the construction of a $130 million, 5 megawatt electric (5-Mwe) test facility at Barstow, California. The tower for this project will be about 500 feet high.

The heliostats of a solar tower will be constructed to meet exacting tolerances. Four different heliostat designs as shown in Figure 12 are presently being tested. All except the Boeing design use steel and glass

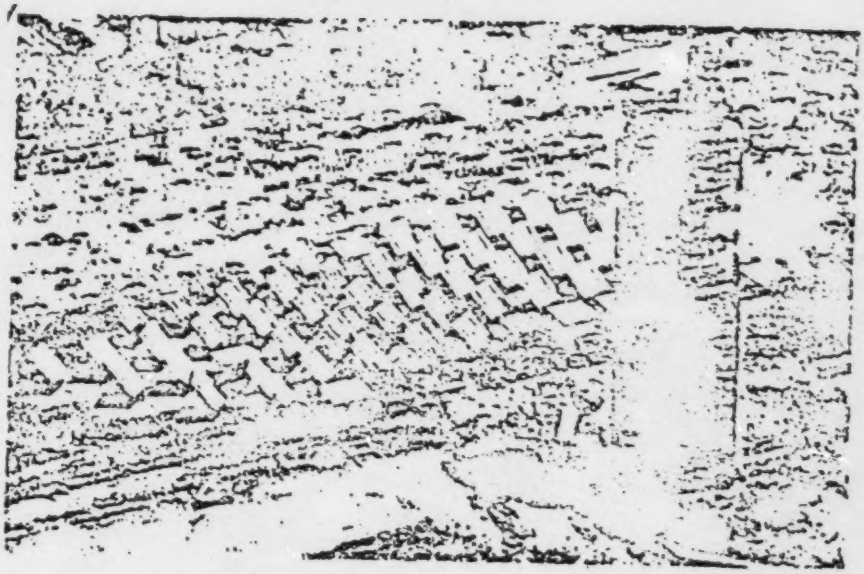


Fig. 11. The Sandia Corporation power tower 5-Mwt test facility of Alburquerque, New Mexico. Seventy-eight heliostats are shown in place, with 200 more to be added. The pickup trucks in the background indicate the scale of the facility.

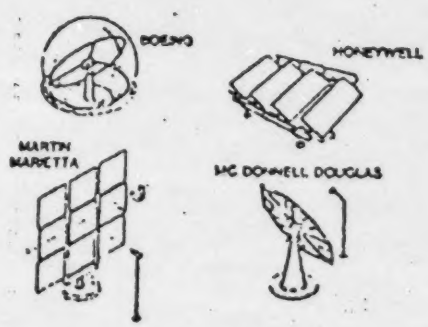


Fig. 12. Heliostat designs under consideration for the 10-Mge solar thermal test plant at Barstow, California.

construction. The Boeing mirror is made of aluminized polyester stretched across a circular frame. Boeing believes that the 20% transmission loss that occurs when sunlight passes through the bubble will be more than compensated for by the cost reduction achieved through the use of lightweight materials. The Honeywell design uses rectangular mirrors mounted on a geared tracking frame that tilts in two directions. The heliostat of McDonnell-Douglas is a solid dish formed of 8 mirror segments. The entire assembly is mounted on a

radar pedestal. Martin-Marietta uses 9 mirrors mounted on a common tracking frame. Present costs for the heliostats are quite high lying in the $500-1000 per square meter range. Estimates of the cost for the solar tower approach all indicate that the heliostats represent 45-50% of the total. Thus, it is imperative to drastically reduce the heliostat costs. The Department of Energy hopes to reduce this to about $70 per square meter. At a cost of $150 per square meter, it is estimated that a plant capital cost of $2000-$2500 per Kwe will be required.

The toughest technical problem to be overcome, however, may be that of the central receiver. Because of the high concentration factor, the power density inside the receiver will be quite high and variable. Some designs affect the focus of different groups of heliostats slightly to spread out the power profile. The materials used in the receiver must be able to withstand instantaneous changes in energy densities from 0-5 MW per square meter. Because of the diurnal variation of the incoming radiation, the system will be subject to frequent temperature cycles. One design concept under study would use a gas, rather than a steam turbine. In this case, the best operating temperature is twice that of a steam turbine. This temperature rules out the use of standard metals in the high temperature face of the receiver; the use of ceramic heat exchanger tubes has been suggested. The use of a dry gas turbine has the strong advantage of reducing the environmental impact as compared to wet systems which will require the importation of water to the site.

e. Heat Storage

A suitable economic way to store energy is crucial to the power development of solar electricity. While the sun is an inexhaustible energy resource, it is also an intermittent one (due to cloud cover as well as its

diurnal pattern). A means of energy storage must be provided to cover the daily variation in the energy output of a solar electric facility. Even during the day there will be fluctuations in intensity. Devising and optimizing the means of energy storage is a problem which will require much future research and development.

The most prevalent type of energy storage system involves the storage of thermal energy as sensible heat, that is, heat is stored by raising the temperature of a given mass of material. Two of the most commonly used materials are rock and water. Water can store about 5 times as much heat as rock for a given ΔT because of its larger heat capacity. However, since, per unit mass, rock (or concrete) is considerably denser than water, there is only a factor of about two difference between the two types of storage on a volume basis. Rock storage has the advantage of allowing more stratification of the heat, thus permitting more efficient extraction of heat from the storage medium. For a high temperature thermal storage water becomes much less attractive because of its low boiling point. Since the ability of iron oxide to store sensible heat is about 90% of that of water on a volume basis, this may be a more attractive approach for high temperature thermal storage of heat. The disadvantages of sensible heat storage systems for large-scale systems are that the storage medium takes up a lot of space and the heat cannot be stored effectively for a long period of time.

Another method of thermal storage is to make use of the latent heat associated with a phase change in a material, such as the transition from a solid to liquid phase. For example, it takes 540 calories to change one gram of water from a liquid to hot steam. Unfortunately, gaseous mixtures are usually difficult to handle so that only materials undergoing a phase change from a solid to a liquid require less energy than for a change from a liquid

to a gas. The heat of fusion of sodium chloride associated with this phase change that occurs near 800°C is only 123 Cal/gram. The advantage of this type of thermal storage over sensible heat storage is that a great deal more heat can be stored in the same volume of material. However, numerous difficulties with this approach remain to be overcome. The materials are usually expensive and corrosive. Some materials have short lifetimes due to decomposition when thermally cycled. Problems associated with super-cooling have plagued the use of these materials in low-temperature applications, as the amount of heat that can be stored decreases after the heat-of-fusion salt has been thermally cycled a few times. For higher temperature applications, eutectic (lowest possible melting point mixture) salts consisting of a mixture of materials (for example, sodium nitrate and sodium chloride) may prove useful.

There are many other energy storage possibilities. For example, storage of mechanical energy by pumping water to a higher elevation is a technique widely used by the power industry to store off-peak power in the eastern part of the country. Another intriguing approach involves the use of rotating flywheels. The stored energy in this approach can be increased either by increasing the mass of the flywheel or by increasing its rotational velocity. Energy storage using batteries would be attractive if the storage capacity of present types could be dramatically improved along with the battery's lifetime under severe usage involving many charge-discharge cycles. For long-term storage the approach of making hydrogen through the electrolysis of water and then recombining water with oxygen in full cells to produce electricity has received considerable attention.

f. Experiment: Cylindrical Reflector

In this experiment we set up a long linear concentrating collector and try to evaluate its concentration factor. A diagram of the suggested apparatus is shown in Figure 13. Essentially what we have is a long cylindrical section with a small cylindrical metal absorber tube located at the focus (radius of curvature divided by two). The cylindrical reflector can be fashioned in any convenient way. For example, one can cut out one-half of a large fruit juice can, or one can find a long parabolic reflecting surface, such as those sold by Edmund Scientific Company. The mounting should be made so that one end can be rotated by hand to track the sun. The absorbing tube should be painted with some type of flat black paint.

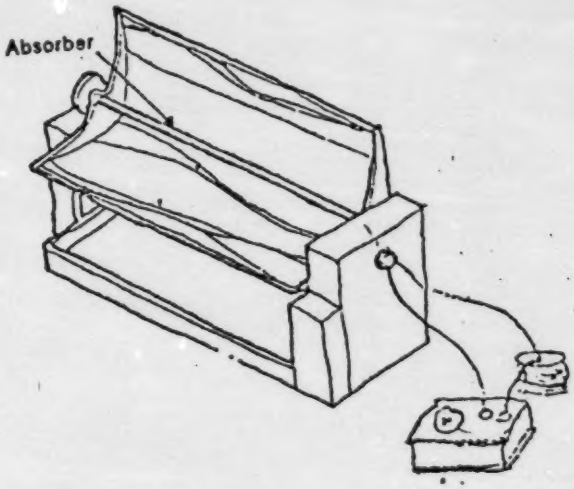


Fig. 13. Schematic illustration of the linear concentrating collector used in this experiment.

The experiment can be carried out as follows. Set up the linear collector near solar noon on a clear day. Connect thermocouple leads to the center of the absorbing rod. The other junction should be placed in a bucket of ice and thermocouple voltage reading read out with a potentiometer. (One can also use a good, modern digital voltmeter, if available.) The cylindrical reflector should then be adjusted to focus the sun's rays on the absorbing cylinder. One simple way to do this is to place a piece of black paper in front of the absorbing cylinder and visually observe the focus. The reflecting cylinder should then be rotated to bring the focus onto the absorbing cylindrical rod. Let the sun's rays warm up the absorber

for 15-20 minutes and then recheck the focus. Measure the temperature every 2 minutes and plot the results. Continue until the equilibrium temperature T_c is reached. Plot this on the abcissa of Figure 9. From the solid dark curve (which corresponds to concentration ratios at which the thermal losses equal the absorbed energy) determine the "measured" concentration factor.

1) Compare this value with the simple calculated value of 2L/d.

2) Your measured value should be higher than the calculated one. Explain why this is so.

3) The curves in Figure 9 were computed for a given set of solar conditions. To check on their validity measure the total solar intensity at noon on a horizontal surface with your solar cell. Use Figure 6 to obtain the direct component on a horizontal surface. This value must now be converted to the actual incident direct solar intensity by dividing by the cosine of the angle made by the sun's rays and the perpendicular to the horizontal surface. (Either measure this or calculate this angle.) Compare this solar intensity with that corresponding to the measured equilibrium temperature using Figure 13.

4) The following simple modification of the above experiment is worthwhile. Encase the metal absorber in glass tubing. Leave the thermocouple leads attached to the metal rod so that its temperature can still be recorded. Then repeat the above experiment noting the maximum temperature achieved. Explain any difference in the maximum temperature.

5) If a parabolic reflector is available, such as that found in a car headlight, the above experiment can be modified by substituting the point-focusing parabolic reflector for the cylinder. The central receiver must now be approximated by a small spherical piece of metal. The size of the spherical absorber can be determined by locating the sun's image on a dark piece of paper.

4. CONCLUSIONS

a. Overview

Although solar thermal power offers great potential as an energy source for the future, there are several problems associated with its widespread implementation. In the following sections we will examine some of these difficulties, and suggest additional sources of information and points to be considered.

b. Physical Limitations of Solar Thermal Electric Power Generation

A prime physical consideration is the amount of space required for a solar thermal power installation. Since the incident energy density is low, solar energy power plants must collect light over an extended amount of area, thereby requiring large initial expenditures for land and equipment.

Naturally, the size of the plant, plus its obvious requirement of maximum solar availability, limits possible plant locations in the United States, primarily such regions as the desert Southwest. Unfortunately, at least for the next decade or two, this means that plants will be located in areas of relatively sparse population. Thus, long power transmission lines will be necessary (and will require additional expense).

A final limitation is the problem of thermal pollution caused by the conversion efficiency limitations of the second law of thermodynamics. Another Issue-Oriented Module, Thermal Efficiencies and Thermal Pollution by Laurent Hodges, treats this problems in great detail for nuclear or fossil-fueled electric power plants. Briefly stated, the problem is that for every megajoule of useful output (electricity), three to four megajoules of waste heat is produced. This waste heat must somehow be dealt with in the local environment of the power plant, typically by using evaporation towers or river water for cooling. Unfortunately, water is a relatively scarce commodity in the region of the United States in which solar thermal power

plants will be located.

c. Economic Limitations of Solar Thermal Electric Power Generation

Meeting the demand for electric power is a complex problem for power companies. They must incorporate a wide variety of energy sources, including coal-fired, nuclear, fossil fueled, gas turbine, hydroelectric, and - possibly - solar thermal, in a way that produces the required power at the lowest possible cost to the power company. Naturally, the variable costs of producing electricity differ widely for the different energy sources. For example, fossil fuel and gas have relatively high variable costs, while hydroelectric and solar thermal are quite low.

Another complicating factor is the daily - even hourly - variation in the demand for electric power. While there is always some minimum demand (called the base load), the maximum demand (peak load) may be four or more times as great. The final complication is that the peak load varies seasonally, which may increase the maximum demand even more. Thus, electric power generation companies must maintain a vast amount of generating capacity over and above that required for meeting the base load.

To best meet the needs of its customers, while attempting to minimize its operating costs, a utility will use its lowest-cost generating facilities to meet as much of the load as possible. Thus, hydroelectric (if any) and nuclear are the first plants to be activated to meet the base load, as they have the lowest operating costs.

Solar thermal also fits into the low operating cost category, but suffers from the diurnal nature of its generating ability. Thus, it cannot be used for base loading. However, most utilities (at least in the Southwestern U.S.) experience peak loading during daylight hours. This happily coincides with the output capability of solar thermal generating equipment. As a result solar thermal would be one of the first sources added to the base load plants

of a utility. (A more complete discussion of this subject will be found in another Issue-Oriented Module, Windpower, by Harry Davitian.)

The other important economic consideration concerning solar thermal power generation is the cost of constructing the solar power plant and transmission power lines. Unfortunately, at the present time these costs are so high that solar thermal power remains economically unfeasible. However, as additional experience is gained from the demonstration projects, and economies of scale begin to apply, the cost per kilowatt of generating should decrease markedly.

d. Questions for Further Investigation

1. Read pages 30-35 and 38-54 of the Davitian Windpower module. Determine how the operating characteristics of solar thermal power generators modify the arguments presented by Davitian. Complete problem 1 on pages 55-56 of Davitian, substituting the words solar thermal for wind or windpower. (This is a valid assumption for the majority of the daylight hours.)

2. Determine the impact on the viability of solar thermal power of the current population trends in the United States. For example, if the "sunbelt" region is undergoing a large increase in population, what implications does this have for Sunbelt electric utilities? What particular areas of the sunbelt region are most likely to develop solar thermal power first? Investigate the impact of this population trend on the electrical requirements of the areas with reduced population - primarily the upper midwest and northeast.

APPENDIX A. REVIEW OF SOME ELEMENTARY OPTIC PRINCIPLES

a. Reflection and Refraction

A very useful property of light can be found by reflecting light from some object. For exmple, suppose that a collimated beam of light is reflected from a polished metal surface as indicated schematically in Figure 7. From the results of many such experiments it is found that when

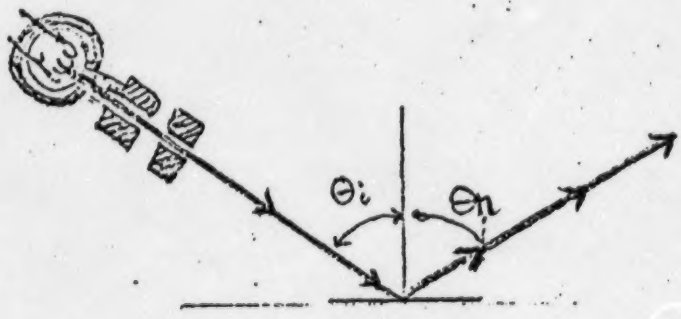


Fig. 14. Illustrating the law of reflection.

light is reflected from a plane specular surface, the incident ray, the reflected ray, and the perpendicular to the surface at the point of contact all lie in the same plane. Even more importantly, it is found that the angle of reflection (θ_r in Figure 14) is equal to the angle of incidence (θ_i in Figure 14).

Another important property of light is illustrated by the changing of direction of light when it passes from one medium to another (both media assumed to be partially transparent). This bending of light is termed refraction. The physical basis for this bending is due to the fact that the velocity of light depends upon the type of medium. Light travels slower in

glass or water than it does in air. A detailed analysis of this effect leads to a relation called Snell's law of reflection,

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i} \quad ,$$

where n_i and n_r are the indices of refraction in the two media ($n_i = C/V_i$).

b. Plane Mirrors

By making a surface of highly polished metal, or by applying a thin metallic coat to a polished surface, the fraction of light reflected can be made to be nearly 100%. A highly reflecting smooth surface is called a mirror. For a plane mirror, an object placed in front of the mirror will appear to lie the same distance in back of the mirror as shown in Figure 15.

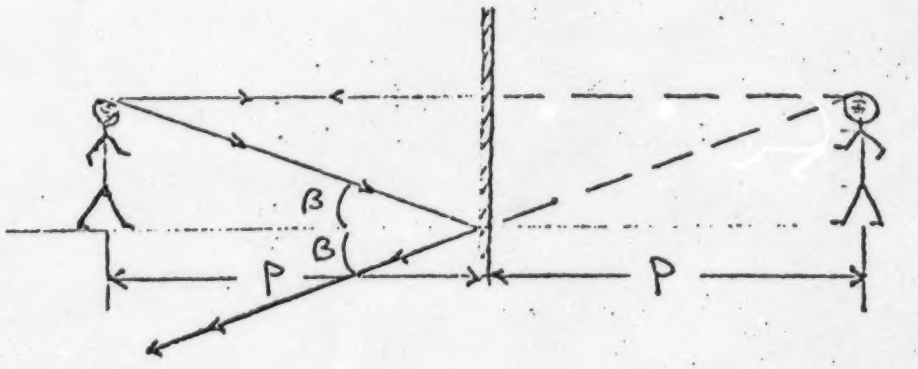


Fig. 15. The law of reflection applied to a plane mirror results in the image lying the same distance behind the mirror as the object in front.

The image one sees in a plane mirror is not a real image but rather is a virtual one. A virtual image is one from which rays seem to radiate but

actually do not. When you see an object in a plane mirror the rays do not come to you directly from the image, instead they reach you by reflection at the plane mirror.

c. Concave Mirrors

A concave mirror is an optical device which can form a real image on a screen (or anything) simply by reflection. This property is utilized in a wide variety of concentrating solar collectors. Let us begin by studying the focusing properties of spherical mirror. A spherical mirror has the form of a circular section of a hollow sphere as shown in cross section in Figure 16. The center point O of the section is called the vertex, and a line from the center of curvature of the sphere through the vertex is called the principal axis. The distance R is the radius of the mirror.

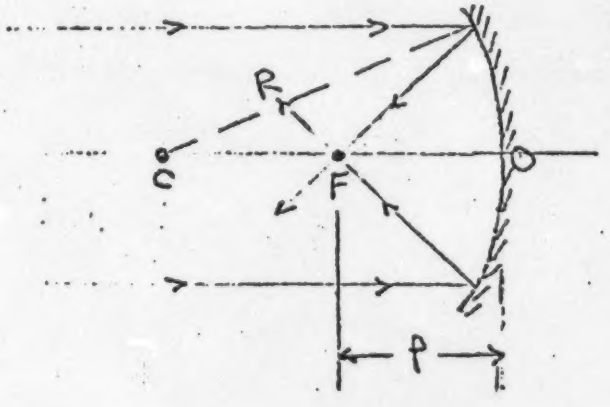


Fig. 16. The center of curvature C, the focal point F, and the focal length F of a concave mirror are illustrated.

In Figure 17 we show how to determine the location of a real image in the case of a concave mirror. The graphical determination of the location and size of the image is done by drawing several key rays.

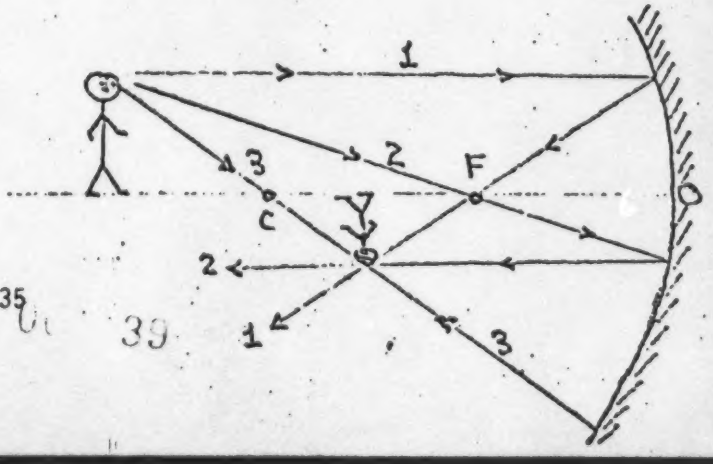


Fig. 17. Diagram showing how to locate the image formed by a concave mirror using the method of principal rays.

These rays are shown on the figure and are:

1) A ray parallel to the axis is reflected through F.

2) A ray passing through F is reflected parallel to the axis.

3) A ray passing through C is reflected back upon itself.

For solar applications we will usually be considering an object located beyond the center of curvature C (the sun is usually the object), in which case the image (real) will always be formed somewhere between F and C.

We can also determine the location of the image analytically using the following mirror equation,

$$\frac{1}{P} + \frac{1}{q} = \frac{2}{R} .$$

In this equation P is the object distance, q is the image distance and R is the radius of curvature, all measured from point O in Figure 17. The distances P and q are positive when measured to the left of the vertex, while R is positive for a concave and negative for a convex mirror.

Exercise 2: Derive the mirror formula using the rules of ray tracing and principles of Euclidian geometry.

d. Parabolic Reflectors

In practice, spherical mirrors are satisfactory only if just a small segment of the actual spherical surface is used as a reflector. If too large a portion of the spherical surface is utilized, then parallel rays from a considerable distance off the principal axis come to a focus at points different from the focal point for rays incident on the mirror at distances quite close to the axis. The focusing defect, called spherical aberration, is illustrated in Figure 18.

This focusing problem can be avoided through the use of a mirror shaped in the form of a parabola. A parallel beam of light incident upon a parabolic reflector is all focused at one point. This is the type of mirror used in spotlights, search lights, and automobile headlights.

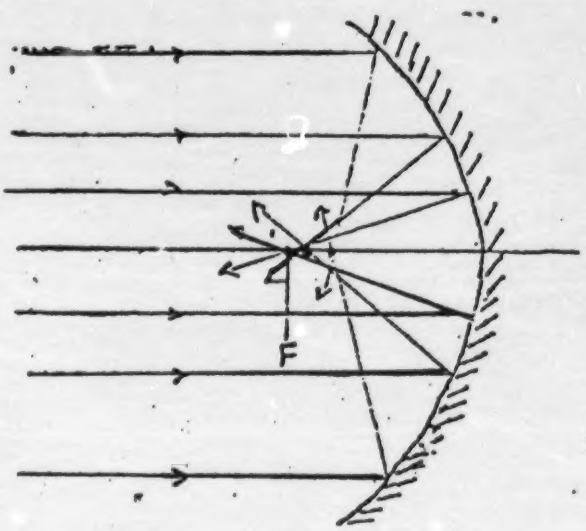


Fig. 18. Diagram illustrating spherical aberration. Rays incident on the spherical mirror at a considerable distance from the axis are focused at points in front of the point F.

e. Example

A concave mirror has a radius of curvature of 30 cm. Find the image of an object oriented perpendicular to the axis of the mirror and located at a distance of 25 cm from the mirror.

The graphical solution to this problem is illustrated above. Note that the image is real, inverted, and is larger than the object. We can check this construction by calculating the location of the image using the mirror equation.

$$\frac{1}{25} + \frac{1}{q} = \frac{2}{30}$$

$$\frac{1}{q} = \frac{2}{30} - \frac{1}{25} \quad , \text{ or } \quad \underline{q = 37.5 \text{ cm}}$$

The positive sign for q indicates that the image is real (located to the left of the mirror on the diagram above.) At this point it is worthwhile to derive the relation between the radius of curvature R and the focal length F for a spherical mirror. An incident parallel beam of light corresponds to a source at infinity. But this beam will be focused at an image distance equal to F. Thus,

$$\frac{1}{\infty} + \frac{1}{F} = \frac{2}{R}.$$

So, $\underline{F = R/2}$

and this fact was used in the above construction.

f. Problems

3-1. While looking at a complicated system of mirror you note that someone else is looking at you. Can he (or she) see you?

3-2. Suppose that your eyes are 150 cm from the floor while you are wearing your normal attire. You are wearing a hat the top of which is 30 cm higher than your eye level. What is the smallest vertical dimension possible for a vertical mirror so that you can just see yourself in the mirror, including your hat?

3-3. A beam of light is incident upon a sheet of plastic, making an angle of incidence of 50°. Part of the beam is reflected and part is refracted. The reflected and refracted beams make an angle of 90° with each other. What is the index of refraction of the plastic?

3-4. When you observe the setting sun in the evening, the time at which the sun actually goes below the horizon is a little before you actually observe this phenomena. Explain this in terms of the refraction of light by the earth's atmosphere.

3-5. An object 10 cm tall is placed on the axis at a distance of 60 cm from a concave mirror with R = 30 cm. Find the location of the image both graphically and with the aid of the mirror equation.

3-6. A concave mirror has a radius of curvature of 30 cm. Find the location of the image for an object placed 10 cm in front of the mirror. Do this both graphically and with the aid of the mirror equation. Describe the image in this case. Would you want to place the lamp bulb for a headlight at this location?

APPENDIX B. HEAT AND THERMODYNAMICS

a. Sensible Heat

It is now understood that heat is a form of energy. More precisely, it is the transfer of energy by molecular collisions. Scientists call the energy content of a substance its internal energy, while saving the word heat for the gain or loss of internal energy brought about by molecular collisions. For example, if hot water comes in contact with cold rock, the water molecules lose energy while the rock molecules gain energy. Energy has been transferred from the hot water to the rock as a result of a large number of molecular collisions. The internal energy of a substance is proportional to the energy of the random motion of the molecules of the material. In turn, this energy of motion is proportional to the parameter we have called temperature.

In the metric system the unit of heat is called the calorie and is defined as the energy required to raise the temperature of 1 gram of water 1°C. In the English system of units, heat was historically measured in British Thermal Units (BTU). This is defined as the energy required to raise the temperature of one pound of water 1°F.

It takes a certain amount of heat to change the temperature of a substance. Formally, this can be written as,

$$Q = CM\Delta T.$$

In this equation M is the mass of the material which has had its temperature changed by ΔT degrees. The constant C, called the specific heat of a substance, is a function of the material involved and it follows from the above definitions that it is unity for water in both the metric and English systems of units.

Since heat is only one form of energy, the heat units of BTU's and calories can be related to work units such as the joule. It was the pioneering work of Count Rumford and Joule which first established the quantitative relation between the two different energy units. Careful experimental measurements established that 1 calorie was equal to 4.18 joules. The calorie has now been redefined to be exactly 4.184 joules.

b. Contrast between Thermal and Mechanical Energy Conversion

It is useful to review the efficiency of various ways of generating electricity. The efficiency of a device is defined as the ratio of useful work output to the total energy put into it. The efficiency of a typical coal-fired electric power generating plant is typically about 40%. This means that 60% of the available stored energy in the coal has been rejected to the outside world. Nuclear reactors commonly have efficiencies in the 32% range, giving an even larger fraction of energy rejected. On the other hand, when water passes over a dam and is used to generate electricity it is found that almost 90% of the gravitational potential energy of the water is converted to electrical energy. This is a tremendous improvement over the other ways of generating electrical power and leads us to ask exactly what is responsible for such wide variation in the efficiency of power generation.

One possible explanation might be that there has been a breakdown in the law of conservation of energy; however, there is no evidence for this in any other experimental observations, so we will rule out this possibility. This is now a great body of evidence showing that the solution to this puzzle lies at a very fundamental level. The lower efficiencies are due to a fundamental thermodynamic limit on the efficiency of conversion of thermal energy to useful work.

c. Second Law of Thermodynamics

The first basic law of thermodynamics simply express the familiar concept of conservation of energy in terms associated with the phenomena of heat transfer. However, it has been found experimentally that the energy conservation idea is not enough to adequately account for the observed facts. On the basis of the first law alone it would be possible for a ship to take in cool ocean water, extract a certain amount of heat, convert this to useful work, and then return the even cooler seawater to the ocean. However, this cannot be done in practice. We call the law of nature that prohibits the above process the second law of thermodynamics.

The second law can be stated in ways which relate directly to the efficiency of a generating plant. Let us go back to the contrast between thermal and mechanical energy conversion. Why is the turbine efficiency so great in the hydro-electric case? The answer is found in the fact that the motion of the falling water is orderly, with the water molecules having a dominant velocity component along the stream flow, so that al of the water falls in a given direction. This is not true for the internal energy of molecules in a hot gas where the motion is random, or disordered. The results of many investigations of thermodynamic processes have shown that nature has a general rule that states that there is a tendency towards disorder, provided that one deals with large enough samples of matter that more than a few molecules are involved. Thus, the second law of thermodynamics can be stated as requiring that order goes to disorder.

Let us review the implications of this statement of the second law. Since mechanical energy of motion is more ordered than is thermal energy, it can always be completely converted into other forms giving rise to the very high efficiency found with hydro-electric turbines. On the other hand, disordered thermal motion cannot be completely converted into ordered mechanical motion. That is, if a fraction of the input thermal energy is converted into useful work (ordered), then the remainder must be discharged in a much more disorderly form (lower temperature) than the input thermal energy. This forces the operating efficiencies of thermally driven plants to be considerably lower than that for hydro-electric plants.

d. Carnot's Relation

The above description of the second law of thermodynamics in terms of ordered and disordered motion is rather abstract. Thanks to the work of a brilliant young French field artillery officer and physicist, Sadi Carnot, the implications of the second law can be formulated in a way which is considerably easier to appreciate. Carnot worked out the relationship between heat and temperature for an ideal engine--one with no friction losses so that the heat level at each end of a thermodynamic cycle would be equal except for that energy extracted to perform mechanical work. The importance of this concept lies in the fact that any real engine has an efficiency which is lower than that for an ideal engine. Carnot found that the efficiency of an ideal engine is

$$\eta_0 = 1 - T_2/T_1,$$

where T_1 is the temperature at the input to the engine and T_2 is the

exhaust temperature. Clearly, an efficient engine needs a hot heat source and the exhaust reservoir should be as cool as possible.

e. Problems

1. What quantity of heat, in BTU, is required to raise the temperature of the water in a 100-gallon hot-water tank from 50°F to 100°F? There are 7.5 gallons in a cubic foot and 1 cubic foot of water weighs 62.5 pounds.
2. A typical house might need about 800,000 BTU/day for space heating in the winter. If the temperature of a water solar storage system is maintained at 140°F, how many gallons of water are needed to store sufficient heat to provide a 3-day supply of space heating? Assume that all energy stored in the water as sensible heat above 80°F can be extracted into the house.
3. Coal contains roughly 12,000 BTU/pound. Suppose that your house requires that 10 tons of coal be burned to provide its space heating needs. If the efficiency of the furnace is 50%, how many BTU's were used to heat the house?
4. A heavy steel rod weighing 100 lbs. is heated to a temperature of 900°F. It is then immersed in an insulated ceramic tank containing 800 lbs. of a certain fluid. The specific heat of this fluid is 0.5 BTU/lb-°F. If the final equilibrium temperature of the fluid and the steel rod is 100°F, what is the specific heat of the steel rod?
5. A Carnot engine whose high temperature reservoir is at 260°F takes in 200 BTU's of heat at this temperature reservoir. Find the temperature of the low temperative reservoir. If the efficiency of a real engine is only

60% of the ideal, how many BTU's/cycle of useful work output are obtained? What is the overall efficiency of the real engine? (Remember that the temperatures in the efficiency equation must be in °K.)

6. A certain ideal engine operates with a temperature for the heat source of 540°C. Operating at a specified exhaust temperature, its efficiency is found to be 30%. If we wish to obtain an efficiency of 50% with the same exhaust temperature, by how many °C must the temperature of the heat source be raised?

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